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Original Article

Burst criterion for Indian PHWR fuel cladding under simulated loss-of-coolant accident

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ABSTRACT

The indigenous nuclear power program of India is based mainly on a series of Pressurised Heavy Water Reactors (PHWRs). A burst correlation for Indian PHWR fuel claddings has been developed and empirical burst parameters are determined. The burst correlation is developed from data available in literature for single-rod transient burst tests performed on Indian PHWR claddings in inert environment. The heating rate and internal overpressure were in the range of 7 K/s–73 K/s and 3 bar–80 bar, respectively, during the burst tests. A burst criterion for inert environment, which assumes that deformation is controlled by steady state creep, has been developed using the empirical burst parameters. The burst criterion has been validated with experimental data reported in literature and the prediction of burst parameters is in a fairly good agreement with the experimental data. The burst criterion model reveals that increasing the heating rate increases the burst temperature. However, at higher heating rates, burst strain is decreased considerably and an early rupture of the claddings without undergoing considerable ballooning is observed. It is also found that the degree of anisotropy has significant influence on the burst temperature and burst strain. With increasing degree of anisotropy, the burst temperature for claddings increases but there is a decrease in the burst strain. The effect of anisotropy in the α-phase is carried over to $\alpha+\beta$-phase and its effect on the burst strain in the $\alpha+\beta$-phase too can be observed.

1. Introduction

Advancement of human civilisation has been energy centric. Energy generation has caused enough degradation of the environment. In present scenario, energy should not be generated at the cost of the earth. Thus, sustainable and clean energy is necessity [1]. In spite of being controversial energy source and having a negative connotation among the certain section of energy policymakers, presently nuclear power seems to be the only viable option that can meet the exponentially rising energy demand in a clean and sustainable manner [2–7]. Perhaps, nuclear alone would not fulfil the global energy demand, but it may not get fulfilled without it [8–10]. Moreover, the role of nuclear power in attaining energy security becomes more crucial for developing countries such as India [11]. Nevertheless, stringent safety criteria and new technologies to make nuclear reactor inherently safe will be the key to its expansion. Public acceptance too is of critical importance for the express expansion of nuclear power, and it shall be attained only with adopting more stringent safety measures to win the public trust [7].

The safety evaluation of any nuclear power reactor during a postulated loss-of-coolant accident (LOCA) and the assessment of its consequences is required for the licensing of nuclear reactor fuel system. LOCA is a major design based accident in a nuclear power reactor during which its fuel claddings are subjected to rapid temperature transients because of loss of coolant caused by breakage or leakage in hydraulic system of the reactor. Fuel cladding which encases the radioactive fuel is the first safety barrier to face adverse consequences of the LOCA [12]. Transient increase in temperature causes the cladding to deform plastically (under the effect of internal gases' pressure) which may also lead to its rupture. That is why for the LOCA safety analysis, a burst criterion model is required to predict the temperature and the time at which fuel cladding ruptures [13].

The indigenous nuclear power program of India is based mainly on a series of Pressurised Heavy Water Reactors (PHWRs). The choice of PHWR was imperative for India because this type of nuclear reactor does not need enriched uranium as fuel and the technology for production of heavy water which acts as its coolant was available [11]. Zircaloy-4 is used as fuel cladding in Indian

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PHWRs because of its strikingly low absorption cross-section of thermal neutrons, apt thermal conductivity, dimensional stability, and corrosion resistance in an exceptionally harsh environment—combination of high temperature, high stress, a chemically corroding coolant, and intense radiation flux [14–16]. These Zircaloy-4 claddings are typically (495–500) mm long and (0.38–0.41) mm thick [11]. Based on power generation rating of the nuclear reactor, Zircaloy-4 fuel claddings are assembled as 19 elements or 37 elements to form fuel bundle.

There is no burst criterion available exclusively for Indian PHWR fuel claddings in open literature to predict the temperature and time for its failure or rupture during the LOCA [17]. Recently Khan et al. [18] conducted the burst investigation on Indian PHWR fuel claddings and proposed a burst criterion for its failure [19]. However, their burst data were too less and limited to only α and α+β-phases of the Zircaloy-4 fuel cladding. Consequently, they had developed burst stress correlation for their criterion using the data obtained by other researchers during the investigations on fuel claddings employed in different types of nuclear reactors. Their criterion was useful from materials perspective but cannot be strictly used as a safety criterion for indigenous Indian PHWRs. Since the burst criterion proposed by Khan et al. [19] may not be truly applicable to Indian PHWR, there was a need to develop a burst test database for the indigenous Indian PHWR fuel claddings especially in its β-phase. Later, Sawarn et al. [17] conducted burst investigations on Indian PHWR Zircaloy-4 fuel claddings at low heating rates and obtained data for β-phase as well, apart from enriching the database of Khan et al. [18] in α and α+β-phases. In another study, Sawarn et al. [20] also reported that the oxidation behaviour of Indian PHWR Zircaloy-4 fuel cladding during postulated LOCA differs from other study conducted on different Zircaloy-4 fuel cladding [21], perhaps it is due to different manufacturing process route [22]. It is thus resolved to develop a more appropriate burst criterion exclusively for Indian PHWR fuel claddings using burst data obtained from investigations performed on Indian PHWR by Sawarn et al. [17] and Khan et al. [18]. The burst criterion has been validated using their experimental data. Moreover, a detailed parametric study has also been conducted to investigate the effect of operating parameters on the rupture behaviour of claddings.

The article is organised in the following way: section 2 presents governing equations used to formulate the burst criterion model. Empirical burst correlation exclusively for Indian PHWR fuel claddings is also developed in this section. Section 3 discusses the numerical algorithm implemented to achieve the solution as well as the validation of the present burst criterion is presented. The effect of different phenomenon on burst behaviour of Indian PHWR fuel cladding is presented in section 4. The research outcomes are concluded in section 5.

2. Governing equations

Zircaloy-4 thin-walled tubes are used in Indian PHWRs as fuel claddings. Zircaloy-4 undergoes phase transformation on heating from α-phase to α+β-phase at around 1093 K and from α+β-phase to β-phase at 1243 K. The structural properties of the cladding in α-phase having hexagonal closed pack structure and in β-phase having body centred cubic structure are quite different [12,15]. This section presents the basic relationships used for developing the present burst criterion for thin-walled Zircaloy-4 fuel claddings.

2.1. Creep of cladding

As already mentioned, the thin-walled Zircaloy-4 claddings are subjected to transient increase in temperature and undergoes plastic deformation or ballooning under the impact of internal overpressure during the LOCA. Subjecting a thin-walled tube to high temperature and an internal overpressure will cause the tube to strain and eventually rupture. The present model assumes that the burst data for internally pressurised Zircaloy-4 cladding can be determined from the steady-state creep equation of the material. The steady-state creep rate of a material at constant temperature and constant stress is usually calculated using the power law-Arrhenius equation— better known as Norton law—which is expressed as [13,14,19,21]:

$$\frac{\mathrm{d}\varepsilon_\theta}{\mathrm{d}t} = A_{\theta_i}\exp\left(\frac{-Q_i}{RT}\right)\ \sigma_\theta^{n_i} \tag{1}$$

where ε_θ and σ_θ is the hoop or circumferential strain and stress respectively, A_θ is the creep strength coefficient, n is the stress exponent, Q is the activation energy, and R is absolute gas constant. i represents phase domain (α or α+β or β) since these parameters are different for each phase of the Zircaloy-4 fuel cladding.

The creep strength coefficient A_θ is dependent on the structure of the material and it is determined from the corresponding uniaxial value A_z which is obtained from the experimental creep investigations. The strength coefficient is calculated using the Hill's relation which is given as [13]:

$$A_{\theta_i} = \left[\frac{1}{4}(F_i+G_i)+H_i\right]^{\frac{n_i-1}{2}}\left(H_i+\frac{1}{2}F_i\right)(F_i+G_i)^{\frac{-(n_i+1)}{2}}A_{z_i} \tag{2}$$

where F, G, and H are anisotropic factors of Zircaloy-4 fuel cladding.

For symmetrical deformation, the instantaneous circumferential or hoop stress σ_θ for thin-walled tube like Indian PHWR fuel cladding under a corresponding differential pressure p is [21]:

$$\sigma_\theta = \sigma_0(1+\varepsilon_\theta)^2 \tag{3}$$

where $\sigma_0 = p_0\cdot\ r_0/s_0$ is the initial hoop stress, p_0 is the initial internal pressure, r_0 and s_0 are the initial outer radius and thickness of the cladding, respectively.

2.2. Burst criterion

Zircaloy-4 fuel cladding bursts whenever the instantaneous tangential or hoop stress exceeds the burst stress—calculated in accordance with following empirical correlation developed by Erbacher et al. [21]:

$$\sigma_{\theta_B} = a_i.\exp(-b_iT) \tag{4}$$

where a and b are the experimentally determined material-dependent constant parameters. This equation points that the burst stress is mainly temperature dependent. However, it is worth mentioning here that these empirically determined constants are the function of the variables like heating rate or investigating atmosphere like inert, air or steam.

3. Computational methodology and model validation

This section explains the numerical framework used —based on the governing equations described in the previous section—to obtain the burst parameters using the burst criterion. The assumptions made, computational approach adopted, parameters or constants used have been presented. The results derived using the model is also validated with experimental data.

3.1. Algorithm

Zircaloy-4 fuel cladding used in Indian PHWR is thin-walled tube. Table 1 reports the dimensions of the claddings along with other test conditions used by Sawarn et al. [17] and Khan et al. [18] during their burst investigations. The initial hoop stress σ_0 is calculated using the as-fabricated cladding's dimensions and initial pressure. For the specified history of temperature $T(t)$ and a given pressure p; the tangential or hoop strain from equation (1) is computed using parameters listed in Table 2 for Zircaloy-4 fuel claddings. The creep strength to be used in equation (1) is calculated with the help of equation (2). Then after, the value of tangential strain obtained is utilised to calculate the tangential stress using equation (3).

The burst data— obtained from the experimental investigations conducted on Indian PHWR fuel claddings by Sawarn et al. [17] and Khan et al. [18] — are used to develop burst stress correlation and accordingly the empirical burst parameters a and b to be used in equation (4) are determined. The evaluation of burst stress correlation using the experimental burst data is shown in Fig. 1. The obtained value of empirical burst parameters a and b is provided in Table 3. Finally, stress required to cause the failure or rupture of the Zircaloy-4 fuel cladding—known as burst stress—is calculated using equation (4) for the temperature at the end of each time step. All these process iterate for the temperature and time history until the instantaneous hoop stress (calculated from equation (1)) surpasses the burst stress (calculated using equation (4)), as it is illustrated and summarised in Fig. 2. The time step used in the computations is 1 ms.

Table 2
Structural dependent parameters for zircaloy-4 claddings [13,21].

Phase domain i	Anisotropic factors			n	A_z (MPa^{-n} s^{-1})	Q (kJ/mol)
	F	G	H			
α ($T \leq T_\alpha$)	0.956	0.304	0.240	5.89	19370	320.0
α+ β ($T = T_{\alpha+\beta}$)[a]	0.5	0.5	0.5	2.33	0.24	102.4
β ($T \geq T_\beta$)	0.5	0.5	0.5	3.78	7.9	142.0

[a] Valid for strain rates $\leq$0.003 s^{-1}, otherwise interpolation is used between α and β-phases.

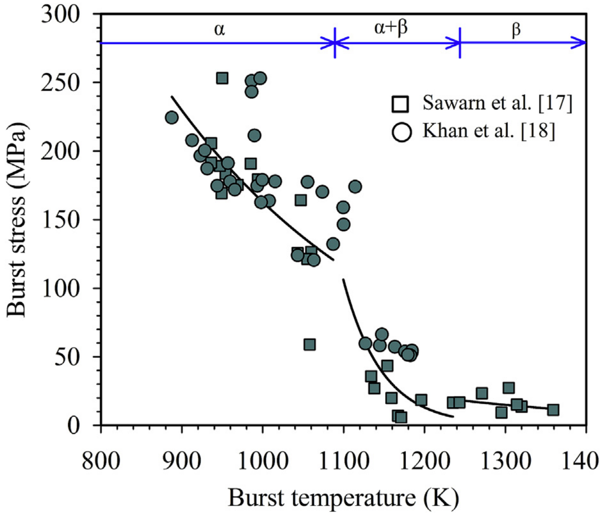

Fig. 1. Development of burst stress correlation for Indian PHWR fuel cladding.

3.2. Model validation

The present burst criterion model has been validated with the experimental data obtained from single-rod transient burst tests performed in inert environment by Sawarn et al. [17] and Khan et al. [18] for Indian PHWR claddings. Sawarn et al. [17] conducted burst tests on the Zircaloy-4 claddings having 15.2 mm outer diameter and 0.4 mm thickness for the heating rate and the internal overpressure ranging from 7 K/s to 12 K/s and 3 bar to 73.5 bar, respectively. Khan et al. [18] used Zircaloy-4 claddings having outer diameter and thickness of 13.08 mm and 0.41 mm, respectively. They varied the heating rates from 17 K/s to 73 K/s and internal overpressure from 20 bar to 80 bar. The rate of heating in both investigations could not be kept constant during burst experiments, a band for it was obtained and accordingly the data were categorised as low: (7–12) K/s, medium: (17–28) K/s, high: (40–55) K/s, and very high: (61–73) K/s heating rates. The typical variations of the temperature and the internal overpressure during their experiments are shown in Fig. 3. For more experimental details, readers may refer [17,18].

For comparison with previous mentioned burst experiments; the Zircaloy-4 fuel cladding with 14.0 mm as outer diameter and 0.4 mm as thickness has been used for the computation. The heating rate and the initial pressure are varied from 1 K/s to 100 K/s and 0.5 MPa to 8 MPa, respectively. The burst parameters obtained from the model, namely, burst strain versus burst temperature (Fig. 4), burst stress versus burst temperature (Fig. 5), burst temperature versus burst pressure (Fig. 6), have been plotted together with the experimental burst data for the comparison. It is evident from these plots that prediction of burst parameters using the present burst criterion is in a fairly good agreement with the experimental data.

4. Results and discussion

This section presents the results obtained using the present burst criterion and discusses them against the backdrop of experimental data. The role of different parameters and phenomena on the rupture behaviour of Indian PHWR fuel cladding during the transient heating is deliberated for understanding the influence of each of them.

Table 3
Empirical parameters for burst stress correlation of Indian PHWR fuel claddings [17,18].

Phase domain i	a (MPa)	b (K^{-1})
α ($T \leq T_\alpha$)	5073.52	0.003
α+β ($T = T_{\alpha+\beta}$)	9980 × 10^8	0.021
β ($T \geq T_\beta$)	1675.40	0.004

Table 1
Details of burst tests conducted on Indian PHWR fuel claddings.

Researcher	Clad material	Clad dimension		Internal pressure (bar)	Heating rate (K/s)	Outside environment	Heating method
		r_0(mm)	s_0 (mm)				
Sawarn et al. [17]	Zircaloy-4	7.60	0.40	3–73.5	7–12	Argon gas	Electrical
Khan et al. [18]	Zircaloy-4	6.54	0.41	20–80	17–73	Argon gas	Electrical

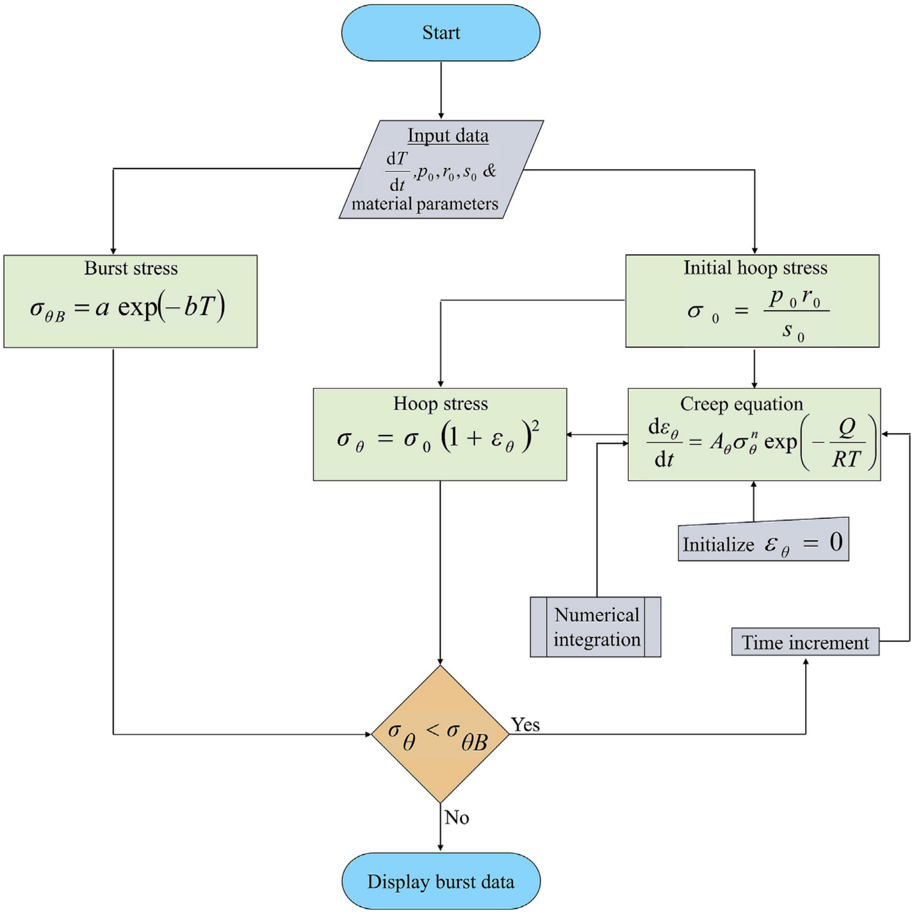

Fig. 2. Algorithm for development of burst criterion model for Indian PHWR fuel cladding.

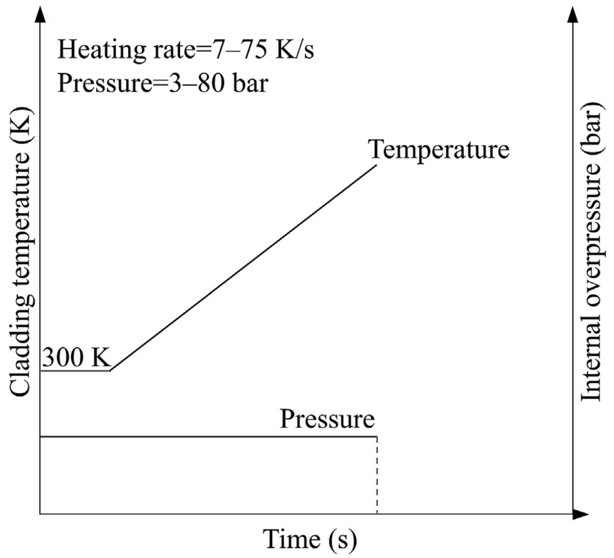

Fig. 3. Typical temperature and pressure variation during the clad burst experiments.

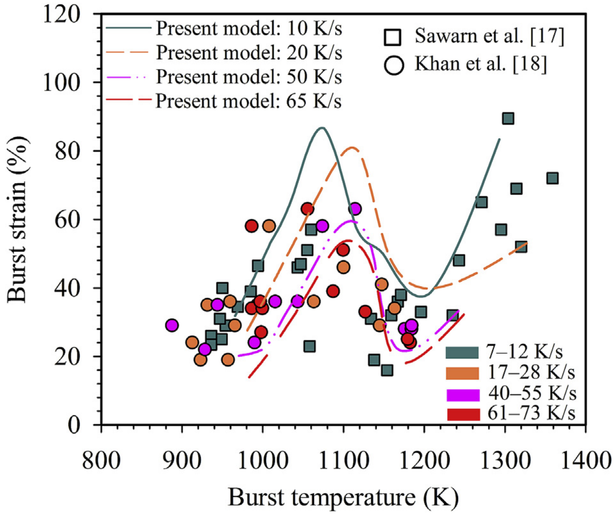

Fig. 4. Validation of burst criterion model: burst strain versus burst temperature.

4.1. *Effect of heating rate and internal pressure*

The rupture or failure time is mainly governed by rate of heating and initial overpressure of the cladding. Fig. 7 shows the variation of burst strain with burst temperature for different heating rates. For a given heating rate, the burst strain increases with the burst temperatures in the α-phase and it attains a maximum near the starting of phase transformation. There is a sharp dip in the burst strain in during first half of the α+β-phase transformation. However, as the burst temperature approaches to the β-phase, the burst strain too approaches to maxima value. Two maxima peaks can be observed more prominently at higher heating rates. Further, it can be also seen

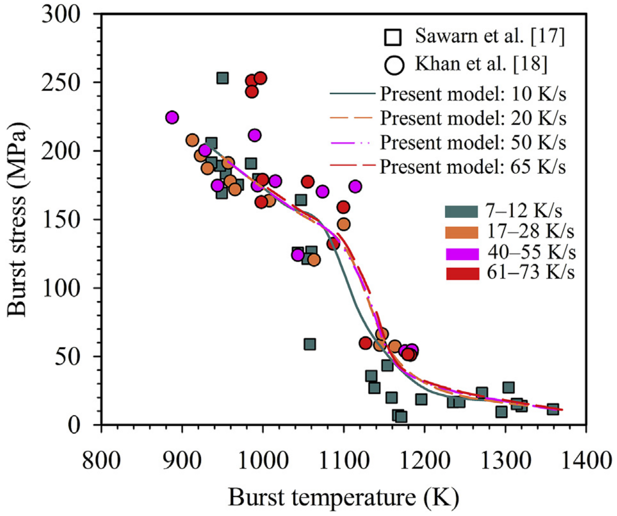

Fig. 5. Validation of burst criterion model: burst stress versus burst temperature.

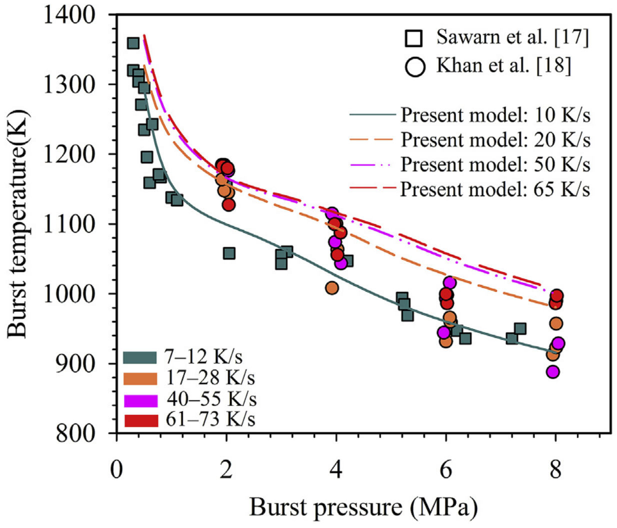

Fig. 6. Validation of burst criterion model: burst temperature versus burst pressure.

that the burst strain is heating rate dependent and it is inversely proportional to it. This is due to the fact that the temperature of the claddings rises too fast to plastically deform or undergo ballooning at higher heating rates and, thus burst earlier. For example, the burst strain decreases from around 140% to 30% when the heating rate is increased from 1 K/s to 100 K/s at α to $\alpha+\beta$-phase transformation temperature. It is also observed, as shown in Fig. 8, that the burst temperature increases with decreasing initial stress for a given heating rate. The burst temperature is low for high applied internal overpressure because it is already strained due to high initial stress and requires very less temperature for rupture. Increasing the heating rate for any given initial stress leads to significantly increased burst temperature. In Fig. 9, the burst stress for different burst temperature is plotted. It is seen that burst stress is lesser for higher burst stress temperature. In order to understand the combined effect of the heating rate and the initial stress, Fig. 10 has been drawn. For a given heating rate, a higher initial pressure results in a lower burst temperature. Burst temperatures increase significantly with increase in heating rate for a given internal pressure, that is, higher heating rates produce higher burst temperatures.

4.2. Influence of anisotropic factors

The creep strength coefficient A_θ is dependent upon the anisotropic factors, see equation (2). There are different values of anisotropic factors F, G, H for the α-phase of Zircaloy-4 claddings according to the treatment it is subjected to Ref. [23]. $\alpha+\beta$ and β-phases are treated as isotropic. The values of anisotropic factors for typical conditions are provided in Table 4 [23]. Fig. 11 has been drawn to illustrate that the burst temperature decreases with stress and the degree of anisotropy has significant influence on the absolute value of the burst temperature. The effect of anisotropy is more prominent at higher initial stress. For an internal overpressure of 8 MPa, the burst temperature can have a maximum difference of around 80 K, only due to anisotropic effect. Fig. 12 illustrates that the effect of anisotropy on burst strain is also considerable. The burst strain is inversely proportional to degree of anisotropy. Near the $\alpha+\beta$-phase transition temperature, burst strain can be reduced from 95% to 45% only due to influence of anisotropy. Another noteworthy observation is that effect of anisotropy in the α-phase is carried over into the $\alpha+\beta$-phase too. However, burst strains are identical in the β-phase.

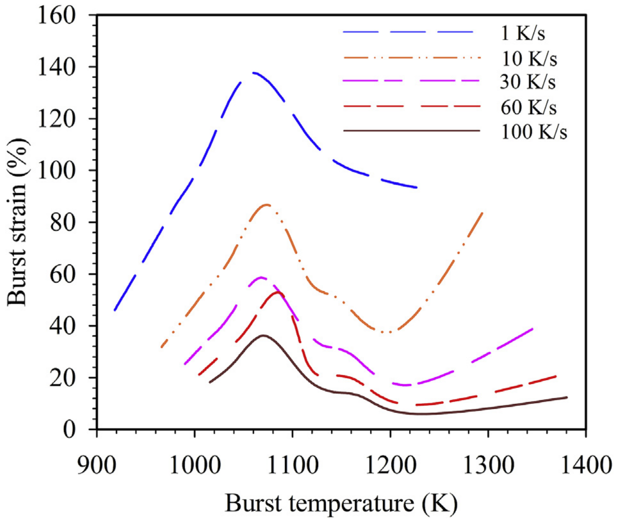

Fig. 7. Burst strain versus burst temperature for different heating rates.

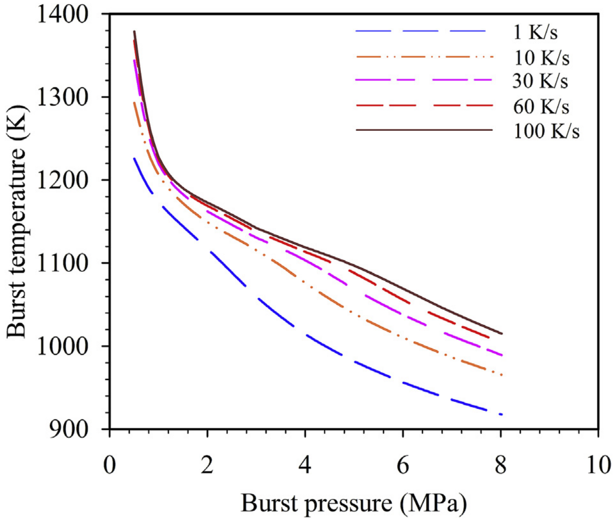

Fig. 8. Burst temperature versus burst pressure for different heating rates.

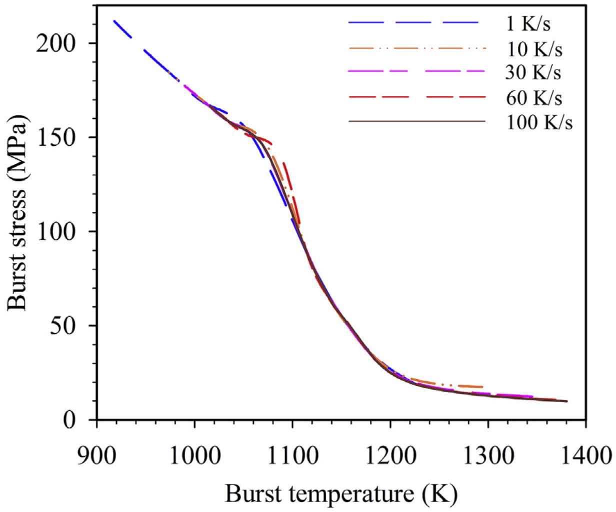

Fig. 9. Burst stress versus burst temperature for different heating rates.

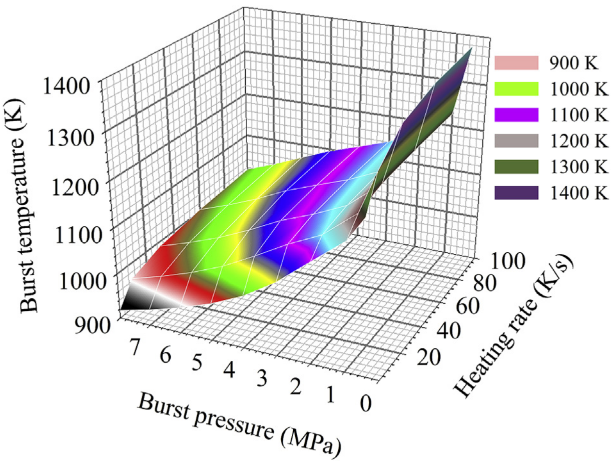

Fig. 10. Burst temperature as function of heating rates and internal overpressures.

Table 4
Anisotropic factors for Zircaloy-4 fuel claddings [23].

Conditions	Anisotropic factors		
	F	G	H
As-received	0.773	0.532	0.195
α-annealed	0.956	0.322	0.222
β-annealed	0.572	0.418	0.510
Isotropic	0.5	0.5	0.5

5. Conclusions

A burst correlation based on the burst data obtained exclusively for the Indian PHWR fuel claddings has been developed and empirical burst parameters have been determined. A burst criterion for Indian PHWR fuel claddings has been developed to predict its rupture behaviour during transient heating in inert environment. The outcomes of the present model are in reasonably good agreement with the experimental results. Following conclusions may be drawn within the scope of the burst criterion developed in the present work:

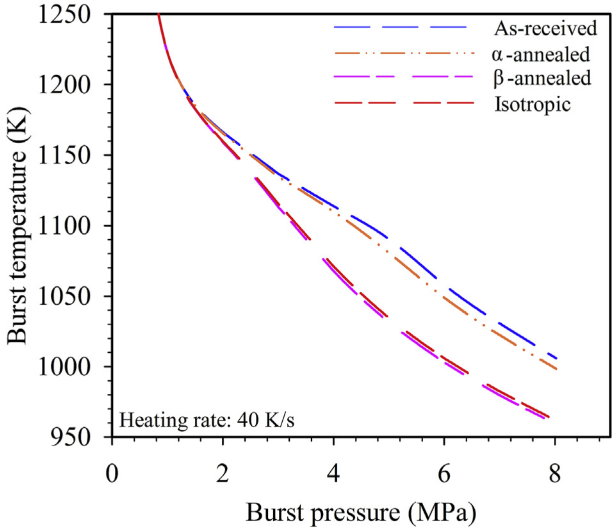

Fig. 11. Effect of anisotropy on burst temperature.

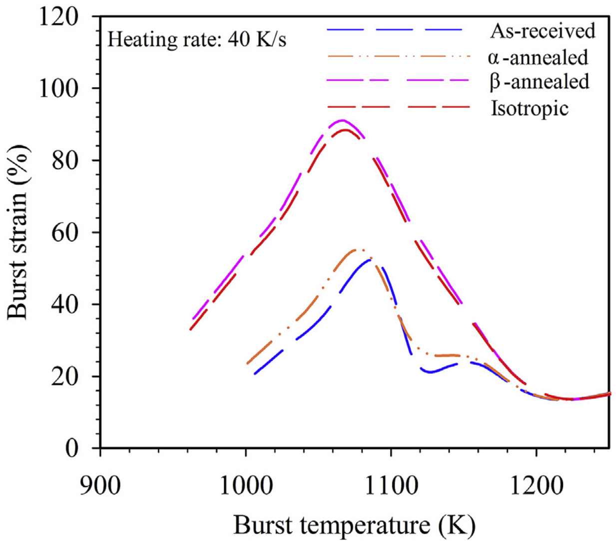

Fig. 12. Effect of anisotropy on burst strain.

•For a given heating rate, a higher initial pressure results in a lower burst temperature. Burst temperatures increase significantly with increase in heating rate for a given internal pressure, that is, higher heating rates produce higher burst temperatures.
•Increasing the heating rate increases the burst temperature. However, burst strain is decreased considerably at higher heating rates which cause early rupture of the claddings without significant ballooning.
•Burst temperature decreases with increasing initial stress.
•With higher degree of anisotropy, the burst temperature for claddings increases but there is a decrease in the burst strain. The effect of anisotropy in the α-phase is carried over to $\alpha+\beta$-phase and its effect on the burst strain in the $\alpha+\beta$-phase too can be observed.

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